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An Analysis of the Primary Energy Consumed by the Re-Liquefaction of Boil-Off Gas of LNG Storage Tank

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Abstract

The pressure in liquefied natural gas (LNG) storage tank continues to increase due to the heat transfer from ambient air to low temperature LNG, which raises safety concerns. This research numerically analyzed the energy consumption of the re-liquefaction of BOG using the following four approaches: 1) a Claude cycle driven by electrical motor with the electricity produced by burning coal; 2) a Brayton cycle driven by a gas turbine fuelled by BOG released; 3) a Claude cycle driven by a SI engine fuelled by BOG; 4) using liquefied nitrogen produced in industry. With the efficiencies of the power system derived from industry data, the energy consumed of the re-liquefaction process was explored. The impact of heat transfer coefficient, LNG tank configuration, size, and percentage of LNG stored in tank on the rate of BOG and energy needed for the re-liquefaction of methane vapor were investigated. The primary energy ratio (PER), defined as the ratio of the energy recovered to the energy consumed, was examined and compared. The highest PER was observed using the Claude cycle driven by internal combustion engine fueled with BOG while the lowest PER was observed when BOG was cooled using liquefied nitrogen approach. The data presented in this paper provides the guideline for the management of pressure development in LNG storage tank and the design of accessory LNG storage system capable of re-liquefying the BOG gas to LNG.

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Keywords: LNG, Boil-off gas, Re-liquiefication, Energy consumption, Primary energy ratio.

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Nomenclature

Q_l	heat from natural gas re-liquefaction	Q_2	engine consumes energy
Q	calorific value of coal	η_1	transmission efficiency
V_1	the use rate of coal		
Q_m	natural gas mass flow	ρ_n	the nitrogen density
h_g	enthalpy of the gaseous natural gas	W	compressor power of Claude cycle
h_l	enthalpy of the liquid natural gas	Q_3	the required liquid nitrogen
Q_l	Brayton cycle consume energy	q_n	the nitrogen flow
η_1	transmission efficiency	η_3	the mechanical efficiency of internal combustion engine
η_2	the mechanical efficiency of the gas turbine		

1. Introduction

Although most liquefied natural gas(LNG) storage tanks are equipped with highly efficient insulation, heat leak from outside occurs unavoidably. Evaporation at the interface of LNG by heat leak leads to the self-pressurization of the LNG storage tank [1-4].Too much boil-off gas(BOG) inside a storage tank brings about safety issues, and too little BOG caused by overrunning of the BOG compressors may mean unnecessary waste of energy[5].The LNG re-liquefaction system has some merit such as large savings in total fuel consumption and improved propulsion redundancy [6][7].

For using different systems to produce the same cooling capacity which is used to the boil-off gas re-liquefaction, the coefficient of performance each system cannot correctly reflect the real performance of the unit. Using the primary energy ratio to compare four kinds of different boil-off gas re-liquefaction systems will be comparable. No researcher do this analyze on primary energy ratio (PER), which defined as the ratio of the energy recovered to the energy consumed. So in this paper, in order to find the optimization cycle for BOG re-liquefaction, it is mainly analyzed about three different power input (electricity, gas turbine and internal combustion engine) for Claude Cycle to liquefying natural gas and they compared with the liquid nitrogen used to liquefying BOG. All the analysis are based on PER.

2. Re-liquefaction System

As shown in Figure 1, the BOG will be condensed in BOG condenser. For this system, some cooling capacity will be given to the heat exchanger. All the system will be described as follows.

2.1. Electricity driven Claude cycle and directly cool the boil off gas by the liquid nitrogen

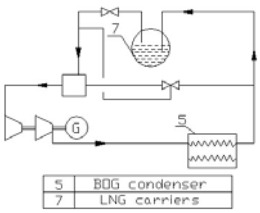

Fig.1 the main BOG re-liquefaction system

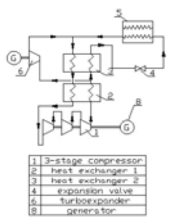

Fig.2 System diagram of the Claude cycle driven by electricity

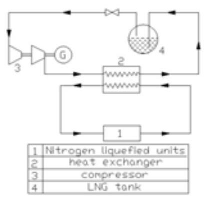

Fig. 3 System diagram of liquid nitrogen re-liquefied the boil-off gas

As shown in Figure 2, the power of the electricity plant directly drives the compressor in the Claude cycle, gaseous nitrogen goes into first the heat exchanger(HX1) after the compressor has a total pressure boost, nitrogen from HX1 is divided into two parts, one part enters the turbine cooler to be cooled, another part of the nitrogen continues entering into the second heat exchanger(HX2) to be cooled into liquid nitrogen (the proportion of the nitrogen after turbine cooler calls the systems bypass rate, which is x=0.55), and then through the throttle valve into the boil-off gas condenser, exchange heat with the gaseous natural gas to be liquefied in BOG condenser(as shown in Fig.1), mix the nitrogen from boil-off gas condenser and the nitrogen from turbine cooler, the mixed nitrogen enters into the HX2, the HX1, finally enters into the compressor to complete this cycle.

The liquid nitrogen(as shown in Fig.3) produced by liquid nitrogen factory directly enters into the heat exchanger, to exchange heat with the BOG from the LNG tank, re-liquefied natural gas transports to the LNG tank, while the nitrogen after heating exchange subsequently enters into liquid nitrogen plant to make re-liquefaction.

2.2. Gas turbine and Internal-combustion engine driven the Claude cycle

The gas turbine (Brayton cycle) dragging the Claude cycle is showed in Fig. 4. The natural gas from the LNG tank is divided into two parts: one part is re-liquefied and goes back to LNG tank, another part of the gaseous natural gas as fuel to provide power for the gas turbine. The output work of gas turbine will drive the Claude cycle to make natural gas re-liquefaction in BOG heat exchanger.

The internal combustion engine system is shown in Fig.5.

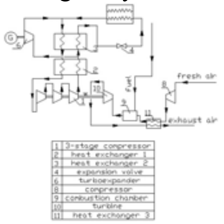

Fig.4 System diagram of Claude cycle driven by gas turbine

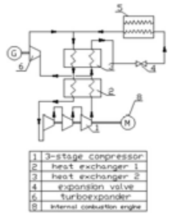

Fig.5 System diagram of Claude cycle driven by internal combustion engine

3. Simulation model

3.1. Electricity driven Claude refrigeration cycle and directly cool the boil off gas by the liquid nitrogen

Obviously the rate of the primary energy of the system is expressed as follows:

$$PER_e = \frac{Q_l}{v \times Q} \tag{1}$$

$$PER_e = \frac{q_m \times (h_g - h_l) \times \eta_1 \times \eta_2}{w} \tag{2}$$

It can be calculated the gaseous natural gas flow per hour, and then calculated the required quantity of heat Q_3, this part heat is absorbed by liquid nitrogen, and then calculate the liquid nitrogen flow that we need. Therefore, the primary energy utilization rate of using liquid nitrogen to cool boil-off gas is calculated by the following formula:

$$PER_d = \frac{Q_l}{Q_3} \tag{3}$$

(4)

3.2. Gas turbine and Internal combustion engine driven the Claude cycle

Using the gas turbine drives the Claude cycle to make boil-off gas liquefied, the heat released from the boil-off gas re-liquefaction is the finally obtained energy Q_l, and the consumption of primary energy of the whole system is gaseous natural gas. Therefore, the primary energy utilization rate of the system is:

$$PER_b = Q_l / Q_1 \tag{5}$$

(6)

Efficiency of the ignition engine is in general 26%-40%, efficiency of the diesel engine is in generally 34%-45%. When using the engine to drive the Claude cycle, it is used by diesel engine to provide power for the Claude cycle. So the energy utilization ratio of the system can be represented by the following formula:

$$PER_n = Q_l / Q_2 \tag{7}$$

$$PER_n = \frac{q_m \times (h_g - h_l) \times \eta_1 \times \eta_3}{w} \tag{8}$$

4. PER analysis

4.1. Relationship between the gas flow,evaporation temperature of the Claude cycle and PER

$$PER_e = \frac{q_m \times (h_g - h_l)}{v_1 \times Q}$$

$$\mathrm{PER}_d = \frac{q_g (h_g - h_l)}{q_n \times \rho_n \times 0.59 \times 3600}$$

It is known from the Fig.6 that with the increasing of natural gas boil-off gas flow, the primary energy rate (PER) of the three systems increases. The highest PER is the Claude cycle driven by the Internal combustion engine.

As shown in Fig.7, it is concluded that along with the increase of the evaporation temperature, the primary energy rate (PER) gradually increases. At the same evaporation temperature, The highest PER is the Claude cycle driven by the engine. For the same natural gas flow rate (i.e. the heat of exothermic liquefaction is certain) and BOG condenser at the nitrogen side has the same inlet temperature, with the evaporation temperature increasing, the power of the compressor becomes smaller, so the primary energy utilization rate increases. But it may not be increased without limit, PER in the range of the calculation temperature is less than 1.

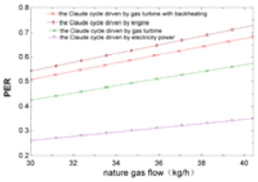

Fig.6 Relationship between the gas flow and the primary energy rate

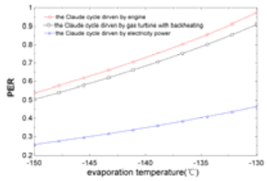

Fig.7 Relationship between evaporation temperature and primary energy ratio

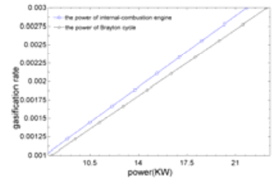

Fig. 8 Relationship between the power and the gasification rate

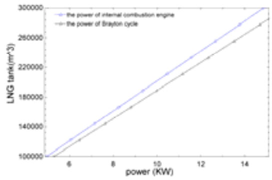

Fig.9: Relationship between the power and the LNG tank volume

4.2. The relationship between the LNG tank volume, BOR and the configuration of gas turbine and engine

When the LNG tank volume is 220,000m^3 ,the gasification rate ranges from 0.1% to 0.3%，the power output of the gas turbine and engine is showed in Fig.8.When the gasification rate of the LNG tank is 0.15%，the volume of natural gas pool range from 100,000 to 300,000m^3 , the power deployment of the gas turbine and engine is showed in Fig.9. As shown in the figures, it can be known that when the LNG tank volume is fixed, with the gasification rate increasing, the power of engine and gas turbine also increases; when the BOR of the LNG tank is certain, with the increase of the LNG tank volume, the power of the engine and gas turbine also increases. But the power of the gas engine is larger than the power of the internal combustion engine.

5. Sample discussion

The design of the LNG boil-off gas re-liquefaction plant has been performed base on the nominal LNG boil-off gas rate (BOR) of 0.15% of cargo capacity per day for a 220,000 m^3 (Full tank filling) LNG carriers. The inlet temperature and pressure of the BOG (boil-off gas) condenser at the BOG side are set to -49.63^{o}C and 3.25 bar, respectively. The outlet temperature and pressure of BOG condenser at the BOG side are -161^{o}C and 3.0 bar, respectively. The characteristics of the BOG and the composition and calorific value of coal are as follows:

Table 1. Characteristics table of the natural gas

	MassFrac. (methane)	Mass Frac (nitrogen)	Mass Frac (ethane)	Temperature (℃)	Pressure (bar)	Density (kg/m^3)	Enthalpy (kj/kg)	Entropy (kj/kg • k)
Gaseous state	0.92560	0.074100	0.0003000	-49.630	3.2500	2.9393	706.58	5.5822
Liquid state	0.92560	0.074100	0.0003000	-161.00	3.0000	434.14	-1.7144	0.36019

Table 2. Properties of coal in China[9][10][11]

Types of coal	Elemental composition							calorific value
	Mar	Aar	Car	Har	Oar	Nar	Sar	(kJ/kg)
blind coalin JingXi	5.0	22.8	67.9	1.7	2.0	0.4	0.2	23040
blind coal in YangQuan	5.0	19.0	68.9	2.9	2.4	1.0	0.8	26400
soft coal in DaTong	3.0	11.7	70.8	4.5	7.1	0.7	2.2	27800

soft coal in XinWen	6.0	18.8	61.0	4.1	6.8	1.4	1.9	25140
soft coal in XuZhou	10.0	13.5	63.0	4.1	6.7	1.5	1.2	24720
Midding coal in LongFengXi	15.0	29.8	42.9	3.4	7.5	0.9	0.5	16760
lignite in FengGuang	22.0	25.7	35.2	3.2	12.6	1.1	0.2	13410

Table 3. Energy consumption of domestic manufacturers of nitrogen production

Factories	Operating cost（kW・h/m^3）
Baode Gas Co. Ltd in Ji'nan.	0.9449
Bao Pu Co. Ltd in Shanghai.	0.648
Air Separation Equipment Co., Ltd in Sichuan.	0.59

According to the given conditions, calculate the primary energy ratios of the four ways are:

The electricity power drives the Claude cycle: PERe=0.3492;

The gas turbine drives the Claude cycle: PERb=0.574;

The gas turbine with regenerative drives the Claude cycle: PERb1=0.684;

The engine drives the Claude cycle: PERn=0.73;

Directly use liquid nitrogen to cool boil-off gas: PERd=0.3657;

According to the theory calculation, it is known that the Claude cycle driven by the internal combustion engine has the maximum primary energy ratio.

6. Conclusion

In this paper, it is introduced and analyzed four kinds of different natural gas (NG) re-liquefaction systems and it is concluded as follows:

(1)For the four kinds of NG re-liquefaction systems, the PER from high to low is:the internal combustion engine drives the Claude cycle to make natural gas re-liquefied, the gas turbine with the regenerator drives the Claude cycle to make natural gas re-liquefied and the electricity drives the Claude cycle to make natural gas re-liquefied and the directly liquefaction system with liquid nitrogen.

(2)When gaseous natural gas flow rate is small, the PER is small; With the increasing of natural gas boil-off gas flow, the primary energy rate (PER) of the three systems increases. The PER from high to low is as follows:the Claude cycle driven by the Internal combustion engine, the Claude cycle driven by the gas turbine and the Claude cycle driven by the electricity power.

(3)In the Claude cycle,with the evaporation temperature increasing, the PER increases gradually.So in the actual operating system, the evaporation temperature of the Claude cycle should be try to raise. But with the limit of the liquefied natural gas temperature, the evaporation temperature cannot increase without limit, in the range of the system design temperature, PER is less than 1.

(4)When the LNG tank and the BOR are certain,the power of the internal combustion engine has the maximum primary energy ratio.

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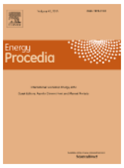

Biography

Professor Shengchun Liu went to the West Virginia University in United States to be a visiting scholar from Feb.,2014 to Aug.,2014.His researches focus on the refrigeration system optimization and energy saving (ice production systems research), heat transfer and heat exchange study on refrigeration and air conditioning systems, performance study of natural refrigerants.